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An Aerospace Requirements Setting Model to Improve System Design

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Abstract

Decisions at an early conceptual stage of the product lifecycle, are made with relatively low confidence, but such decisions greatly influence the overall product and service development. It is, therefore, critical to define the risks involved in order to help designers to make informed decisions. This research project investigates the risk and uncertainties in delivering products to meet top-level business requirements. The aim is to improve the existing process of setting business requirements and the current design approaches to achieve an optimised system design. This project also examines different approaches in assessing the risk of product and service delivery. To achieve that, a dedicated software tool, based on Weibull distribution function reliability model, has been created.

An example of Rolls-Royce Civil Large Engine (CLE) gas turbine design process is used in this research as the case study. An analysis of the gap between the current design achievements and the targeted business requirements of a new product is performed at whole engine, module and component level. Further comparison of the new product business requirements, the novelty in the design and the historical reliability data is used to define and assess the risk of new product delivery.

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Keywords: Risk, System Design, Weibull Distributions, Business Requirements, Decision – Making.

1. Introduction

The design phase is a crucial stage in the life cycle of a product. Some studies reflect that 70% of the production cost is determined during the conceptual design phase [1]. Moreover, decisions during this stage are made with the least amount of confidence, but have a large impact on the overall aircraft engine development. The design phase is one of the riskiest stages, as it is the one that has more uncertainties. It is crucial to make the best decisions possible, as they will be critical in the future design of engines.

Designers have to meet business requirements and explore all possible solution based on a collection of historical knowledge. Risk of satisfying the requirements has to be assessed in order to devise the best solution. Conceptual design stage must also be able to demonstrate a need for future improvements in the company, by identifying the weaknesses of current designs.

The aim of this study is to assess the gap between the current design achievements and the targeted business requirements. Time on Wing of an aerospace engine is the main business requirement assessed in the developed model. Indeed, when a new aircraft engine is introduced into an airline fleet, one of the first questions asked is what will be the average time (hours) between overhaul or refurbishment of the different parts of the engine. Typically, for a new engine program, the airlines bring the engines in early for overhaul, for example, approximately at 10,000 hours [2].

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When an aircraft engine is removed for service for cause and shipped to the refurbishment shop, the engine and the performance of its individual modules are evaluated and the root cause of removal determined. If the engine is removed for performance or major part failure, the engine will be, in most cases, completely broken down into modules: such as compressor, turbine and auxiliary gearbox [2].

The objective of the present work is to develop a software-tool enabling to assess the feasibility of satisfying a defined Time on Wing. The assessment is carried out by breaking down the engine into modules and components, and analysing the in-service data through Weibull distributions. These distributions enable to make predictions about the product's life and its reliability.

The remainder of the paper is organized as follows: Section 2 presents the results of the related research done, the fundamentals of the Weibulls analysis and the main features of the aircraft engines. Section 3 will present the model developed as well as the software-tool. Finally, discussion and conclusion will be summarized in section 4.

2. Related Research

2.1. Weibull Distribution

Weibull analysis is one of the most common statistical approaches used when predicting failures. It is the leading method for fitting and analyzing life data. This analysis uses failure reference and mean-time-to-failure (MTTF) to forecast. The Weibull Distribution used in this paper is defined by two parameters, β the shape or slope parameter, and η the characteristic life parameter of the distribution.

The first parameter β, the slope of the Weibull distribution, is really important as it would indicate the class of failure that describes the data. Figure 1 shows the different failure mode depending on the value of β. This parameter also indicates whether the failure rate is constant or increasing or decreasing if β= 1.0, β >1.0, β <1.0 respectively [3]. If β<1 it indicates that the product has a decreasing failure rate. This scenario is typical of "infant mortality". If β=1 it indicates a constant failure rate. In this case failures are random and are not controlled. If β>1 it indicates an increasing failure rate. This is typical for products that are wearing out. A high scale parameter or steep slope is usually desirable, as the studied element is more predictable. To summarize:

- β < 1 indicates infant mortality;
- β = 1 means random failures;
- β > 1 indicates wear-out failures.

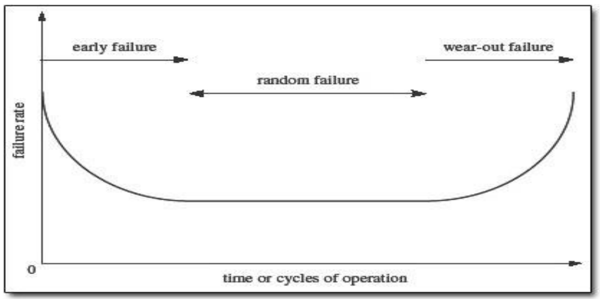

Figure 1: The “Bathtub curve” failure modes [4].

The second parameter η, usually called the characteristic life it is related to the Mean-Time-to- Failure (MTTF). It is defined as the value in time by which 63.2% of all failures will have occurred [5].

The Weibull distribution or the Cumulative Distribution Function (CDF) used is expressed as:

$$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} \quad (1)$$

Where again β and η are slope parameter and the characteristic life described before. Equation (1) can be in linear form by taking two times the natural logarithms of both sides.

$$lnln\left(\frac{1}{1-F(t)}\right) = \beta \ln t - \beta ln\, \eta \quad (2)$$

The CDF equation can now be rewritten as: $y = \beta x - \beta ln\eta$. This is now a linear equation, with a slope of β and an intercept of $\beta ln\eta$. The x-axis is simply logarithmic, since $x = \ln t$. The y-axis is slightly more complicated, since it must represent $y = lnln\left(\frac{1}{1-F(t)}\right)$.

2.2. Aircraft Turbofan Operating Temperatures

Gas turbine engines power most commercial flights operating today. These engines composed by more than 30, 000 components, operating above their melting point, propel aircrafts upwards and onwards [6]. The technology used in these engines is complex as they have to operate reliably in exceedingly hostile environments where temperature and pressure vary dramatically in different parts of the engine.

Today’s engines can experience turbine inlet temperatures in excess of 1,500°C. Figure 2 shows the temperature rise through the engine gas flow path. The engine´s components are exposed to different environments, thus each one need to have different characteristics in order to operate reliably [7].

Modules situated close to the combustion chamber (High Pressure Turbine and High Pressure Compressor) are the ones that are exposed to the most hostile environment, where pressure can go up to 40 atm and temperature to 1,500 ºC [8].

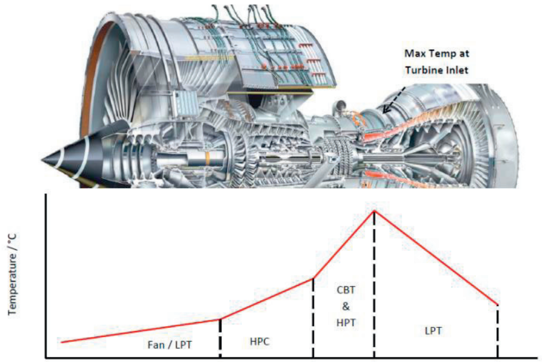

Figure 2: Temperature distribution in an aircraft engine.

By understanding the environment where the different modules and components are exposed it is possible to find a relationship between the Weibull parameters, and the pressure and temperature profiles of the engine. Indeed, usually when the environment is hostile the slope of the Weibull distribution β tends to be high and the characteristic life η low. The slope of the Weibull parameter tends to be high as the failures are due to a specific cause rather than being uncommon.

3. The developed Weibull Distribution Model

3.1. Introduction to the model

The main objective of the developed Weibull Distribution Model is to determine the risk of delivering a product according to a given requirement. In this paper the requirement studied is Time on Wing desired by an aircraft company, defined as the average time (hours) between overhaul or refurbishment of the engine.

The risk assessment is performed by taking the given business requirement, and by collecting the historical knowledge altogether with novelty. The analysis has been carried out by breaking down the engine into modules and components.

The input of the model is the business requirement, Time on Wing, and the output is the gap between the requirement and the current design performance. Figure 4 shows the analysis followed in the model. A software-tool enabling to use the model has also been developed.

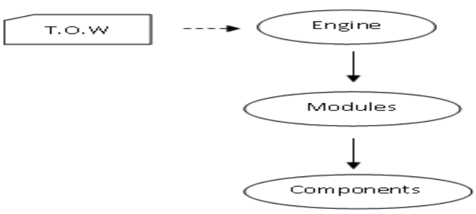

Figure 4: Model Analysis.

The data used by the model is based on *Dinesh Kumar et al.* [9] which focused on a Rolls-Royce Turbomeca Adour Engine. This paper is using a Rolls-Royce Civil Large Engine (CLE) gas turbine as the case study. Figure 3 shows a schematic diagram of the studied engine, which is composed of eight modules. The time to failure distribution of the various modules and their parameter values are given in Table 1. The data in Table 1 is fictitious and any resemblance it may bear to any past, present or future engine is purely coincidental. The results explained in this paper will be based on this data.

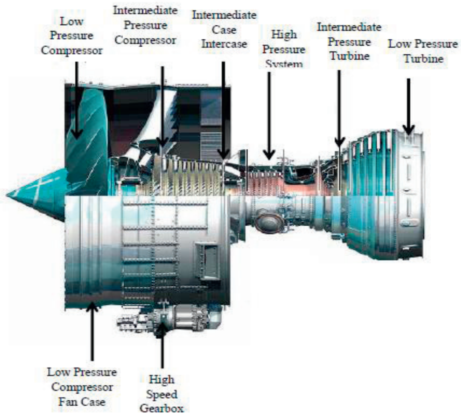

Figure 3: Engine Modules.

Item	*Distribution*	*Parameter Values*
Low Pressure Compressor	Weibull	η= 8,200 FH ; β=1,4
Intermediate Pressure Compressor	Weibull	η= 9,300 FH; β=2,2
Intermediate Case Intercase	Weibull	η= 4,200 FH; β=3,7
High Pressure System	Weibull	η= 3,200 FH; β=4,1
Intermediate Pressure Turbine	Weibull	η= 8,600 FH; β=2,7
High Speed Gearbox (HSGB)	Weibull	η= 12,600 FH; β=2,4
Low Pressure Compressor fan case	Weibull	η= 8,500 FH; β=2,8
Low Pressure Turbine	Weibull	η= 6,400 FH; β= 2,2

Table 1: Time-to-failure distribution of the different modules of the engine.

It has to be noted that the Weibull parameters shown in Table 1 are the parameters of each module, which are the composite of the different components parameters of the given module.

Table 1 also illustrates that the module which is exposed to the most extreme conditions, high temperature and pressure, is usually the one that has the lowest characteristic life η and the steepest slope β.

Weibulls Distributions are common statistical distributions used in companies such as Rolls-Royce, where they perform accurate reliability studies analysing the different components of the engine through these representations. The data required by the model is therefore available in such companies.

3.2. Engine Breakdown

The developed model studies the feasibility of achieving a desired Time on Wing using a top down approach. This approach allows identifying the modules and components that are critical for the engine, thus the ones that impede to meet customer's requirements.

The first step is to study the historical in-service data of each of the modules and analyze if the performance of each of them could satisfy the new requirements. In case that one or more modules do not meet the requirements it is important to study in detail these modules and determine the critical components. It has to be noted that novelty will also be considered in the risk assessment. Figure 5 shows the different steps followed. The software-tool developed also clearly shows the breakdown of the engine.

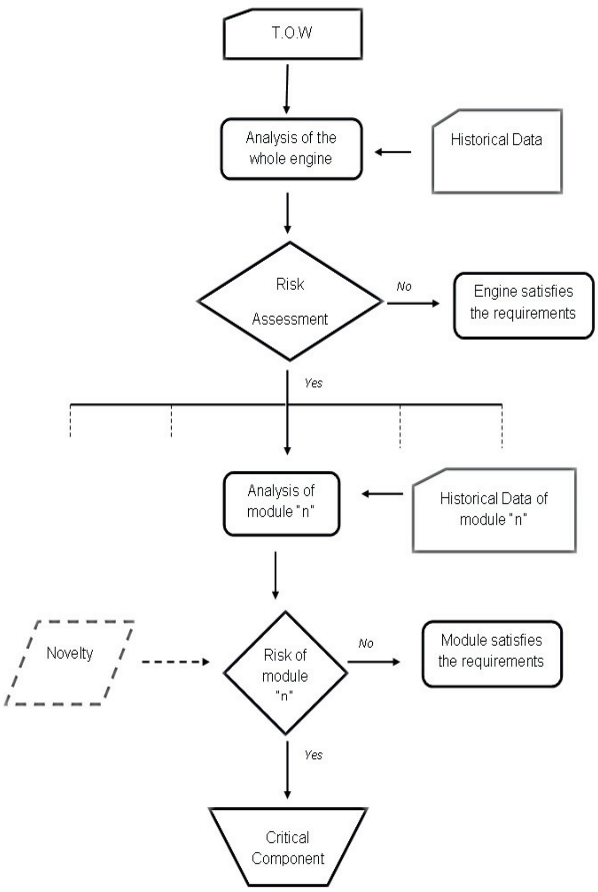

Figure 5: Steps of the developed model.

3.2. Module Level

In order to determine the critical modules, a box plot analysis has been carried out as shown in Figure 6. Mean Time to Failure of each of the different modules is required for the development of these statistical representations. This statistical analysis is a simple and visual technique that allows identifying the critical modules that have to be analysed in order to determine the critical components. Critical modules are the ones that based on historical data do not have the capabilities for meeting the new customer requirements.

The software-tool includes the box plot analysis of the Mean Time to Failure of each of the modules. Figure 6 shows the analysis realized with the developed tool of the studied engine. The Time on Wing required in this case is 4,500 flying hours. In this example, two modules do not have the capabilities for satisfying the requirement, as their current design has never lasted the new required time. This would indicate the need of improvement of these modules in order to be able to satisfy customer needs.

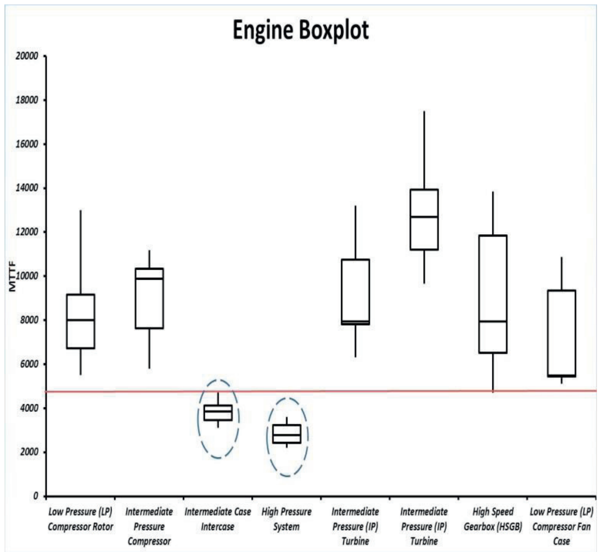

Figure 6: Boxplot representations of the Mean Time to Failure of each Module.

Indeed, these boxplot representations easily enable designers to detect where the risks are, and therefore enable to focus on the modules concerned, in this case the Intermediate Pressure Compressor and the High Pressure System. The data taken in the examples are based on the Weibull parameters shown in Table 1.

3.3. Component Level

Once the critical modules have been identified, they have to be studied in more detail. For studying a module, Weibull Distributions are produced, based on equation (2), in order to describe the failure distributions. The data required in this case are the Weibull parameters, β and η, coming from the in-service maintenance data, of the components of the module. The main components that can drive the engine out of the wing when they fail are plot through Weibull Distributions.

Besides identifying the critical component, the model also enables to understand the gap between the current design achievements and the required performance of the engine. Indeed, this gap is given as the characteristic life η that the critical component should have in order to achieve a desired Time on Wing and Reliability. The Weibull parameter β, the shape, is a physics parameter depending on the environment, and so cannot be controlled and modified. On the other hand, the characteristic life η, can be enhanced by improving the technology of the product. Therefore, the level of risk is evaluated depending on the gap between the current characteristic life η of the component and the desired one.

3.4. Components Analysis of Critical Modules

Figure 7 and 8 illustrates two different examples of Weibull Distributions, developed with the software-tool, analysing three components of a module. This analysis focus on the High Pressure System, one of the critical modules as observed in Figure 6. Both examples analyse the same components using different Weibulls parameters, β and η.

Figure 7 shows that component 1 is the critical component of the module. Indeed, the critical component is the one that has more probability to fail in a given time. Plotting the Time on Wing required at 4,500 flying hours, the probability of failing of this component after having flown 4,500 hours is 55 %, thus the reliability is 45% as illustrated in Figure 7.

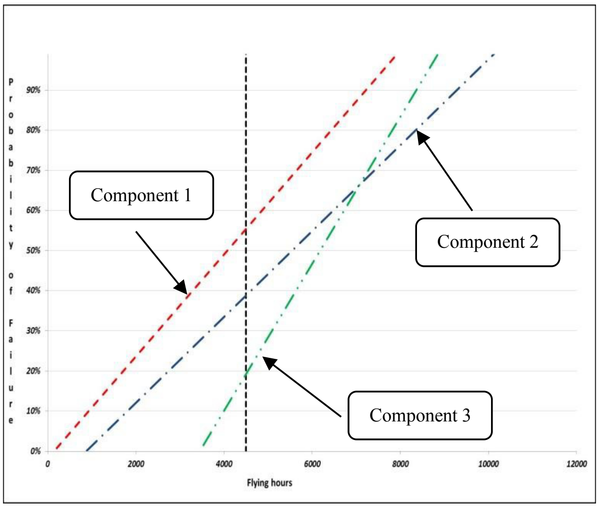

Figure 7: Weibull analysis 1.

The example shown in Figure 8, analyzing the same components than in Figure 7 but using different parameters, illustrates that in this case the Weibull distributions of the different components intercept in different points. Therefore, the critical component varies with the time. Indeed, component 1 is the critical component until 5,200 flying hours, then component 2 leads the failures of the module and finally since 5,900 flying hours component 3 is the critical one. By plotting the Time on Wing at 4,500 flying hours, the critical component is again component 1, as for this given time is the one that has the highest probability to fail. In this case the probability of failing is 57%, and so the reliability is 43%. In order to meet the required Time on Wing, component 1 is the critical one, and so is the one that has to be enhanced.

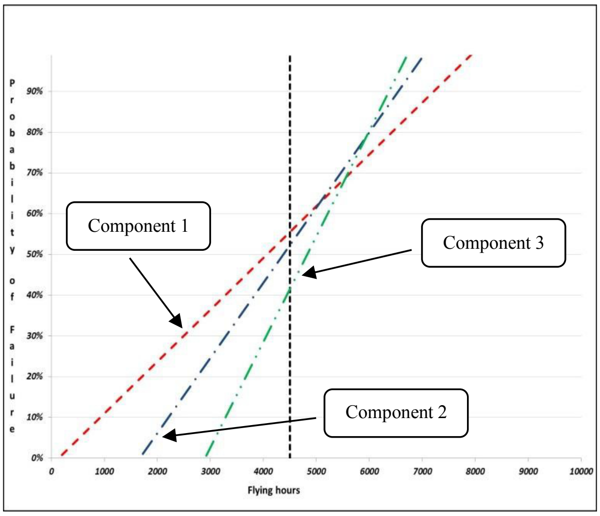

Figure 8: Weibull analysis 2 modifying β and η.

In the software-tool, once introduced the Time on Wing and the reliability required, two plots are built, a plot including the Weibull Distributions of the main components, as shown in Figure 7 and 8 , and a Reliability Plot as illustrated in Figure 9.

The reliability plot describes the probability for a module of surviving a given Time on Wing. The reliability of the module is determined by the critical component, and thus the parameters can vary with the time as shown in Figure 9. Taking as an example the three components analysed through Weibull Distributions in Figure 8, where the critical component varies with the time, it can be observed that at time 5,200 and 5,900 (where the Weibull distributions intercept) the reliability curve change its slope, as the critical component changes, and thus the parameters of the critical component.

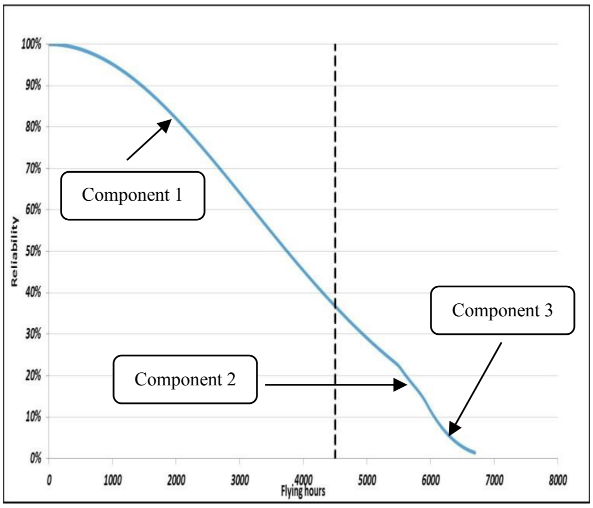

Figure 9: Reliability plot referred to the 2nd Weibull analysis.

Figure 10 describes the inputs required by the software-tool in order to analyse the previous example (shown in Figure 8 and 9). Three components with different parameters, component 1 β=2 and η= 4,500 hours, component 2 β=3.5 and η=4,900 hours and finally component 3 β=6.2 and η= 4,900 hours, are studied. The requirements are a reliability of 80 % and a Time on Wing of 4,500 flying hours.

Component 1		
	BETA	2
	ETA	4500
Component 2		
	BETA	3.5
	ETA	4900
Component 3		
	BETA	6.2
	ETA	5300

T.O.W required	4500
Reliability Required	0.8

Figure 10: Inputs required by the software-tool for the 2nd analysis.

The different outputs of the software-tool are the current reliability, the critical component and its Weibull parameters, and finally the characteristic life η required in order to satisfy the Time on Wing and Reliability required by the customer. The two plots are then built and the outputs are calculated as shown in Figure 11. The current reliability for the required Time on Wing is 43%, component 1 is the critical component and the characteristic life η required for the component in order to satisfy the requirement is 9,526 flying hours. The characteristic life η required in order to satisfy the requirement is more than twice higher than the current η and therefore it is considered risky to satisfy the new requirements with the current design achievements.

Results	
Reliability	0.43
Critical Component	Component1
Beta critical	2
Eta critical	4500
ETA REQUIRED	9526.21422

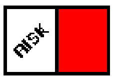

Figure 11: Outputs given by the software-tool for the 2nd analysis.

In order to meet the desired requirement an iterative process has to be followed. In this case, the characteristic life of component 1 should be enhanced to 9,526 flying hours, and then it has to be reviewed which of the components becomes the critical one, and so follow an iterative process.

4. Conclusions

This paper has presented a developed model which provides a simple and efficient assessment of the risk associated in developing a new product. Indeed, this software-tool facilitates decision-making at early design stages by enabling designers to take decisions with more confidence.

The developed software-tool is found to be very helpful in assisting designers to quickly identify the most critical components of an aircraft engine.

Moreover, by understanding the gap between the current performance and the targeted business requirements enables to identify the weaknesses of the current product, thus the areas of improvement needed by the company.

On the other hand, this model is mainly based on Weibull Distributions, and therefore it requires understanding of this statistical distribution and knowledge of the different failure modes. Besides, in order to successfully use the tool, accurate reliability data has to be available.

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